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John A. Barnden and Christopher A. Fields
Co-Principal Investigators

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1. Summary

This project comprised two related research efforts:

- (A) high-level connectionist cognitive modeling,
- (B) local neural circuit modeling.

The goals of the first effort were to develop connectionist models of high-level cognitive processes such as problem solving or natural language understanding, and to understand the computational requirements of such models. The goals of the second effort were to develop biologically-realistic models of local neural circuits, and to understand the computational behavior of such models.

In keeping with the nature of NASA's Innovative Research Program, all the work conducted under the grant has been highly innovative. For instance, the following ideas, all summarized below, are novel contributions to the study of connectionist/neural networks:

- the *temporal-winner-take-all*, *relative-position encoding*, and *pattern-similarity association* techniques
- the importation of *logical combinators* into connectionism
- the use of analogy-based reasoning as a bridge across the gap between the traditional symbolic paradigm and the connectionist paradigm
- the application of connectionism to the domain of belief representation/reasoning.

The work on local neural circuit modeling also departs significantly from the work of related researchers. In particular, its concentration on low-level neural phenomena that could support high-level cognitive processing is unusual within the area of biological local circuit modeling, and also serves to expand the horizons of the artificial neural net field.

As well as numerous publications and presentations, several Master's theses and Doctoral dissertations were partially supported by the grant. The grant was also part of the impetus behind the production of three books in a series edited by Barnden for Ablex Publishing Corporation. In addition, a small business was set up, and a patent filed.

2. Achievements on (A): High-Level Connectionism

2.1. Winner-Take-All Networks

Barnden created and investigated the “temporal-winner-take-all” (TWTA) mechanism for achieving selection of units/tasks in neural networks. The mechanism is described in: Barnden, Srinivas & Dharmavaratha (1990); Barnden & Srinivas (in press); Srinivas & Barnden (1990); and Srinivas 1991.

The TWTA mechanism exploits temporal differences among the *arrival times of signals* on connections as the means for making selections, as opposed to using activation differences as in the various conventional types of winner-take-all (WTA) mechanisms widely used in neural networks. The TWTA mechanisms has several advantages over conventional WTA techniques. In particular:

- it does not require a slow relaxation process;
- it does not require a large number of extra connections;
- it does not require exact comparison operations between activation levels;
- it does not require as much in the way of parameter adjustments to cope with different numbers of contenders;
- and it inherently provides an indication of when it has finished the selection process.

The TWTA mechanism requires several rounds of contention in general. However, the expected number of rounds is merely logarithmic (roughly speaking) in the number of contending units.

The TWTA mechanism is an important element in Barnden’s neural net framework, Conposit. It represents a particular instance of our approach of establishing the relevance of detailed, low-level neural effects to high-level information processing. In fact, as discussed below, the mechanism also played an important role in the work on goal (B) of our research (Local Neural Circuit Modeling).

TWTA is especially well suited to cases where an *arbitrary* selection from among some contending units or subnetworks must be made. This is a common type of selection operation in the Conposit system.

A detailed unit-level program for simulating the TWTA mechanism was written and tested. It was validated by comparison with the results of a detailed mathematical analysis of the system by Srinivas and Barnden.

As part of our investigation of TWTA, we conducted a simulation study of various WTA mechanisms described in the literature. The experiments confirmed our expectations that conventional WTA mechanisms are subject to important limitations such as instability, slow convergence, difficulty in detecting termination, and over-sensitivity to the number of contending units.

The experiments on conventional WTA and on TWTA formed the backbone of Srinivas' Ph.D. dissertation. The TWTA mechanism also played an important role in the Master's theses of two other research assistants, Randall Findley and Mark DeYong, and in DeYong's Ph.D. dissertation.

2.2. Rule-Based Reasoning Version of the Conposit Framework

Under the grant, major developments were completed on a structured (though not classically localist) connectionist framework for connectionist rule-based reasoning. The culmination of this work was a system called Conposit/SYLL. This system implements syllogistic reasoning through the manipulation of Johnson-Laird mental models. The intention was not to extend or test the Johnson-Laird approach as a psychological theory. Rather, the goal was to verify and demonstrate the capabilities of some unusual connectionist techniques for representing complex information structures. These techniques are *Relative-Position Encoding* and *Pattern-Similarity Association*. The system also demonstrates the application of the Temporal-Winner-Take-All mechanism for selection among contenders (see above). One broad issue raised is the way in which the particular nature of these techniques affects what it is natural to do at the symbolic level of description. In particular, the techniques predispose the system towards random as opposed to pre-ordered sequencing of subtasks, and towards associative linking of symbolic structures as opposed to use of explicit linking constructs. The system is elaborate, but this is because it is designed for procedurally elaborate reasoning tasks. The mental model processing achieved is one of the most complex types of symbolic processing to be tackled in connectionism.

Conposit/SYLL is described in Barnden (forthcoming, b). Other papers on the Conposit framework are Barnden (1989), Barnden (1991a), and Barnden & Srinivas (1991).

2.3. ABR-Conposit: Analogy-Based Version of Conposit

The Conposit framework was later developed in the direction of case-based reasoning and analogy-based reasoning, leading to a system called ABR-Conposit (initially called CBR-Conposit). One motive was to correct Conposit's main deficiency, namely its lack of learning facilities. However, an equally important motive was the goal of gaining both the standard advantages of connectionism and those of symbolic systems (without adopting hybrid

symbolic/connectionist systems).

We adopted fully connectionist systems that support analogy-based reasoning as a novel way of achieving that goal, at least in the realm of high-level cognitive processing. This domain includes common-sense reasoning and the semantic/pragmatic aspects of natural language processing. ABR-Conposit, purely by being analogy-based, gains forms of graceful degradation, representation completion, similarity-based generalization, learning, rule-emergence and exception-emergence. The system therefore gains advantages commonly associated with connectionism, although the precise forms of the benefits are different. At the same time, through being fully connectionist, the system also gains the traditional connectionist variants of those advantages, as well as gaining further advantages not provided by analogy-based reasoning per se. And, because the system is in part an implementation of a form of symbolic processing, it preserves the flexible handling of complex, temporary structures that are well supported in traditional artificial intelligence and which are essential for high-level cognitive processing.

Although the system has not yet been fully implemented, headway was made on the connectionist implementation of the long-term memory of source analogs (cases) central to any analogy/case-based reasoning system. Also, we partially implemented a novel connectionist mechanism for matching two complex symbolic structures with each other. Such matching is also central to analogy/case-based reasoning systems. Our matching mechanism rests on the use of compressed encodings (reduced representations) of the symbolic structures. (These encodings had already been added for independent reasons to the rule-based Conposit framework, at a late stage of its development.) The matching is essentially a relaxation process, but instead of working by means of mutually influencing, scalar activation values, it works by means of mutually influencing, *vector* activation values, namely the compressed encodings. Thus, the compressed encodings involved in the two structures being matched are gradually adjusted during matching. To our knowledge, this is an unprecedented way of exploiting connectionist compressed encodings.

The compressed encodings are also the crux of the process for retrieving source analogs from the long-term memory. The compressed encodings allow retrieval to be sensitive to complex symbolic structures, not just to individual atoms in those structures.

The ABR-Conposit approach is described in Barnden & Srinivas (1992a), Barnden (in press, b), and Barnden (in press, c).

2.4. Variables, Logical Combinators and Connectionism

Connectionist attention to variables has been too restricted in two ways. First, it has not exploited ways of doing without variables in the *symbolic* arena. One variable-avoidance method, that of *logical combinators*, is particularly well established there. Secondly, the attention has been largely restricted to variables in long-term rules embodied in connection weight patterns. However, *short-lived* bodies of information, such as sentence interpretations or inference products, may involve quantification. Therefore, the question arises of whether

short-lived activation patterns need to achieve the effect of variables.

We have analyzed some benefits and drawbacks of using logical combinators to do without variables in short-lived encodings while not losing any expressive power. One benefit is that they make encodings and transformations of them qualitatively more uniform and easier to devise. The uniformity stands also to facilitate parallelism. Another benefit is that in certain circumstances combinators lend extra efficiency to mechanisms that match short-lived encodings with each other. Such matching is important in high-level cognition. The main drawback is that combinators can make symbolic expressions bigger.

The work on this topic has so far been mainly theoretical (although we did implement a small prototype of a connectionist combinator-based system). The work is reported in Barnden & Srinivas (1990) and Barnden & Srinivas (1992b).

2.5. Connectionism and Belief Processing

The systematicity and structure-sensitivity of high-level cognition, notably common-sense reasoning and natural language understanding, are widely recognized to present a challenge to connectionism. However, there is an aspect of systematicity and structure-sensitivity that has not been adequately addressed by either side of the symbolist/connectionist debate. A system must have a way of *embedding* reasoning within various types of context. Notably, a system must be able to reason within the context of another agent's beliefs.

We analyzed some of the embedding aspect of systematicity, concentrating on the case of belief. We identified a considerable challenge that it presents to connectionist systems that work by learned holistic processing of compressed encodings (reduced representations). Such systems have been shown to have considerable promise for providing systematicity and structure-sensitivity while avoiding a straightforward implementation of traditional symbol manipulation. Our work leads to a more balanced view of that promise while being sympathetic to the paradigm.

We have also analyzed some technical aspects of the representation, in connectionist cognitive agents, of the propositional attitudes (beliefs, etc.) of other agents. This work has been focused mainly on connectionist systems that do not directly implement symbolic representations. One prominent way of symbolically representing attitudes is through *meta-representational* schemes. These have representational expressions that themselves refer to representational expressions. Meta-representation is one of the most expressively powerful symbolic approaches for attitude representation. Therefore, we have the question of whether non-implementational connectionist systems could use an analogous approach.

Unfortunately, it is not straightforward to devise a plausible analogy to symbolic meta-representation. We have looked at three main possibilities: (i) the representational activation patterns of the non-implementational connectionist system refer to the system's own activation

patterns; (ii) the activation patterns refer to formal symbolic expressions; and (iii) the activation patterns refer to natural-language expressions. We claim that possibility (iii) avoids some of the problems of (i) and (ii), and also has benefits that are independent of specifically connectionist considerations. The analysis highlighted the point that even a non-implementational connectionist system must be able to make inferences *about* complex symbolic constructs such as logic expressions and natural language phrases, even though it does not make inferences *with* them.

The work on connectionism and beliefs is reported in Barnden (1991b, 1992a,b,c,d), Barnden (in press, a), and Barnden (forthcoming, a).

3. Achievements on (B): Local Neural Circuit Modeling

The research effort in low-level, local neural circuit modeling was focussed on the development of electronic circuit models of processing elements that simulate neurons, components of neurons, or small groups of neurons.

Our first modeling goal was to develop realistic models of relatively simple pattern-generating circuits such as are found in invertebrates. We developed circuit models of all of the major components of a generic spiking neuron: excitatory and inhibitory chemical synapses, the dendritic tree, the soma, the axon hillock, and the axon. The behavior of these models under a range of conditions was simulated using the general analog circuit simulation program SPICE, version 3c. The component models were used as building blocks to construct circuit models of central pattern generators, logic elements, and Temporal-Winner-Take-All decision networks.

The electronic circuit models employ conventional CMOS, and in some cases BiCMOS, integrated circuit technology, and are intended for fabrication as VLSI devices. The models preserve both the pulse shapes and relative timing of both action potentials and post-synaptic potentials (PSPs) observed in neurons; however, these are linearly scaled from the mV - ms voltage and time domains to the V - ns domain. This scaling substantially decreases the noise sensitivity of the models, and allows the use of designs having smaller numbers of devices, while increasing the speed with which computations can be performed by approximately six orders of magnitude.

We developed a set of second generation models that allowed all of the major model parameters - the amplitudes and widths of the PSPs and the threshold and timing of action potential firing - to be varied adaptively. Both purely CMOS and mixed CMOS - BiCMOS versions of these circuits were developed; these have the advantages of easier fabrication and higher speed, respectively. These adaptive circuits have allowed us to investigate relatively slow forms of learning such as implemented by conventional artificial neural networks, as well as rapid forms of neural modulation observed in nervous systems. We also started an investigation into the utility of these models for implementing nearest-neighbor classification algorithms, which have been used successfully for a wide range of pattern recognition, time-series

prediction, and motor control tasks.

The work is reported in the papers by DeYong, Fields and/or Findley in the publication list below.

The Temporal-Winner-Take-All mechanisms is important in both branch (A) and branch (B) of the research supported by the grant, and features in DeYong's thesis and dissertation. It provides a salient instance of the way in which low level neural phenomena, such as the fine signal timing differences exploited by temporal-winner-take-all, can make an important contribution to high-level connectionist modeling.

4. Personnel

The project personnel were as follows:

John Barnden, PI.

Christopher Fields, PI.

Imre Balogh, Graduate Research Asst, Ph.D. student in Computer Science.

Mark DeYong, Graduate Research Asst, M.S. student in Electrical and Computer Engg.

Randall Findley, Graduate Research Asst, M.S. student in Electrical and Computer Engg.

Kankanahalli Srinivas, Graduate Research Asst, Ph.D. student in Computer Science.

Heather Pfeiffer, Graduate Research Asst, Ph.D. student in Computer Science.

Thomas Eskridge, Graduate Research Asst, Ph.D. student in Computer Science.

5. Landmark Events

(1) Mark DeYong and Randall Findley, research assistants on the project, obtained their Master's degrees from the Department of Electrical and Computer Engineering in Spring 1991. DeYong later went to receive his Ph.D. on an extension of the master's work. The three theses were on topics central to effort (B) and were based directly on their work as Research Assistants on the project.

(2) Kankanahalli Srinivas obtained his Ph.D. degree from the Department of Computer Science in Spring 1991. His dissertation was on the topic of winner-take-all networks, which is central to effort (A) and also connects to part of effort (B). The dissertation was based directly on his work as a Research Assistant on the project. The abstract is appended to this report.

(3) Imre Balogh is close to obtaining his Ph.D., for research based on the connectionism/beliefs work described under (A) above. Balogh was a research assistant on the

grant.

(4) The grant research was partially responsible for leading to the production of a book (Barnden & Pollack) consisting of a collection of chapters on the area of effort (A). Most of the papers were written especially for the book.

(5) The book mentioned in (4) is the first volume in a series entitled *Advances in Connectionist and Neural Computation Theory*. Barnden is the Series Editor. The second and third volumes are currently in press, for publication near in the Fall of 1993. See the Holyoak & Barnden and Barnden & Holyoak items in the publication list below. The volumes are tightly linked, and are edited collections of papers on the question of applying connectionism to analogy-based reasoning, case-based reasoning and metaphor. All the chapters were written especially for the volumes.

(6) In May 1992, a patent was filed by New Mexico State University on work resulting from aspect (B) of the grant research. The patent title is "Asynchronous Temporal Neural Processing Element." The patent is pending.

(7) Mark DeYong (a research assistant on the grant) set up a small business, Intelligent Reasoning Systems, as a spin-off of aspect (B) of the grant research. The business is currently funded by three SBIR grants — one from the NSF and two from the Department of Defense.

5.1. Publications

Barnden, J.A. (1989). Neural-net implementation of complex symbol-processing in a mental model approach to syllogistic reasoning. In *Procs. 11th Int. Joint Conf. on Artificial Intelligence* (Detroit, August 1989). San Mateo, CA: Morgan Kaufmann. pp.568-573.

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Barnden, J.A. (1992b). Beliefs, connectionism, meta-representation, vagueness: stirring the pot. In *Working Notes of Symp. on Propositional Knowledge Representation*, AAAI Spring Symposium Series, Stanford University, March 1992. pp.19-28.

- Barnden, J.A. (1992c). Connectionism, structure-sensitivity, and systematicity: refining the task requirements. *Memoranda in Computer and Cognitive Science*, No. MCCS-92-227, Computing Research Laboratory, New Mexico State University, Las Cruces, NM 88003.
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- Barnden, J.A. (in press, c). On the connectionist implementation of analogy and working memory matching. To appear in Holyoak & Barnden (in press: see below).
- Barnden, J.A. (in press, d). Time phases, pointers, rules and embedding. *Behavioral and Brain Sciences*. Invited Commentary (on Shastri and Ajjanagadde's "From Simple Associations to Systematic Reasoning").
- Barnden, J.A. (forthcoming, a). How might connectionist systems represent propositional attitudes? To appear in V. Honavar & L. Uhr (Eds.), *Artificial Intelligence and Neural Networks: Steps Toward Principled Integration, Volume I: Basic Paradigms; Learning Representation Issues; and Integrated Architectures*. Cambridge, Mass.: Academic Press.
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- Barnden, J.A. & Holyoak, K.J. (Eds). (in press). *Advances in Connectionist and Neural Computation Theory, Vol. 3: Analogy, Metaphor and Reminding*. Norwood, N.J.: Ablex Publishing Corp.
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